Pion Production and the Pion Form Factor

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motivation

method

results and future

data on ^{2}H

high $|t|$

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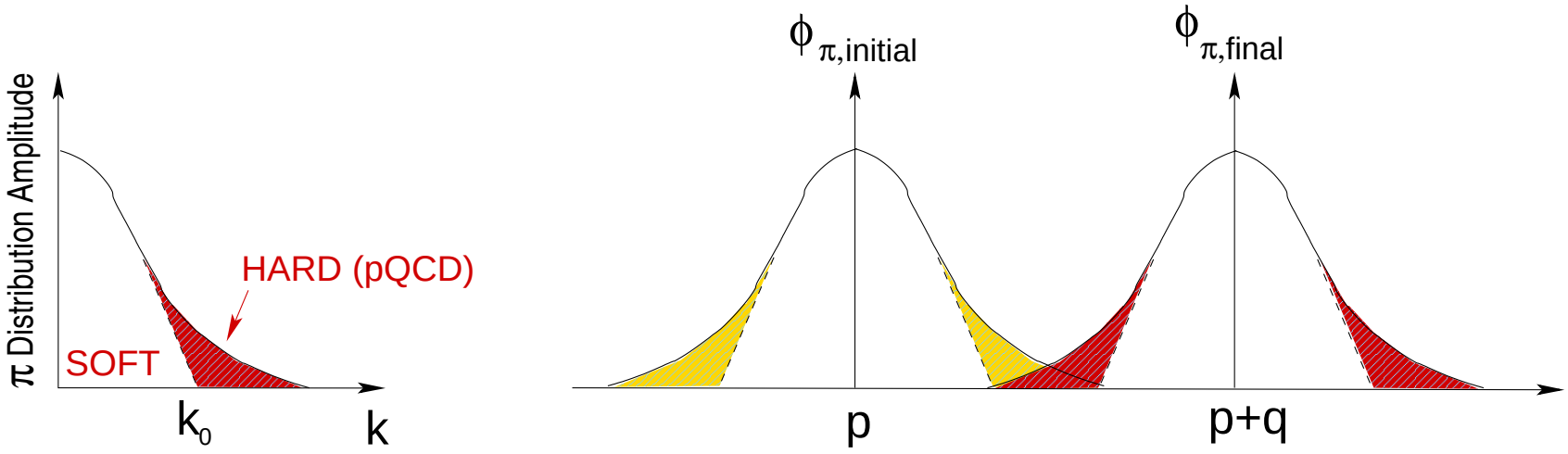
The Pion Form Factor in QCD

F_{π^+} has a unique place in our quest to understand hadronic structure, as the $\bar{q}q$ valence structure of the π^+ is relatively simple.

In quantum field theory, the pion form factor is given as the overlap integral

$$F_{\pi^+}(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$



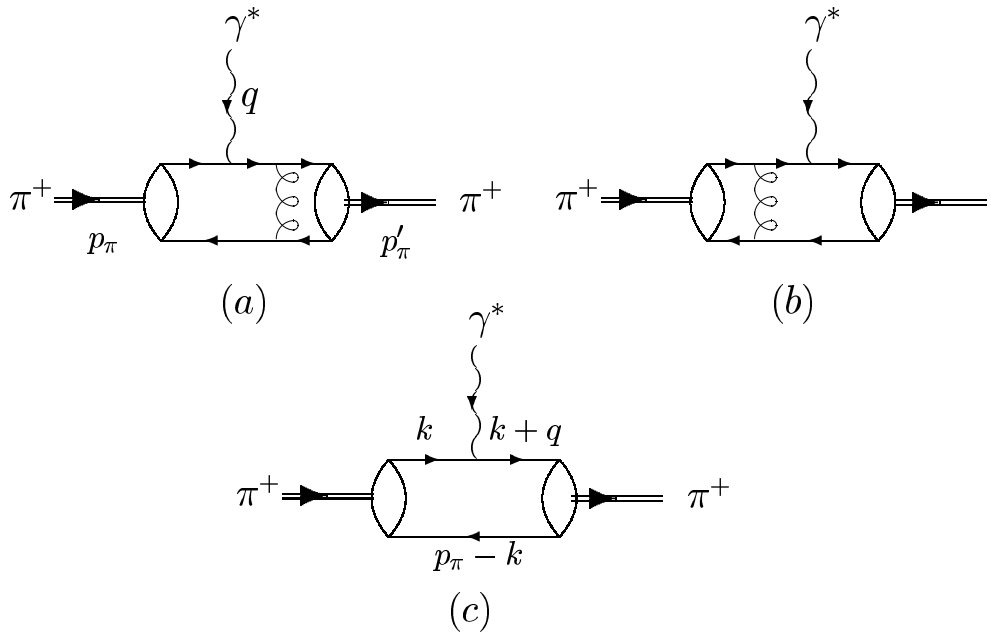
The pion wave function can be separated into a ϕ_π^{soft} part with only low-momentum contributions ($k < k_0$) and a hard tail ϕ_π^{hard}. While ϕ_π^{hard} can be treated in pQCD, ϕ_π^{soft} cannot.

From a theoretical standpoint, the study of the Q^2 dependence of F_π focusses on finding a description for the soft and hard contributions to the pion wave function.

QCD Hard Scattering Picture:

At very high Q^2, perturbative QCD (pQCD) can be used.

$$F_{\pi^+}(Q^2) = \int_0^1 dx \int_0^1 dy \frac{2g^2}{3xyQ^2}\phi(x)\phi(y)$$



$g^2 = \frac{4}{3}\pi\alpha_s$ ($q-g$ coupling const)^2

xyQ^2 virtuality of exchanged gluon.

As $Q^2 \to \infty$, only the hard portion of the wave function remains

$$\phi_\pi(x) \to 6 f_\pi x(1-x)$$

where f_π determines the asymptotic normalization of the wave function from $\pi^+ \to \mu^+\nu_\mu$ decay.

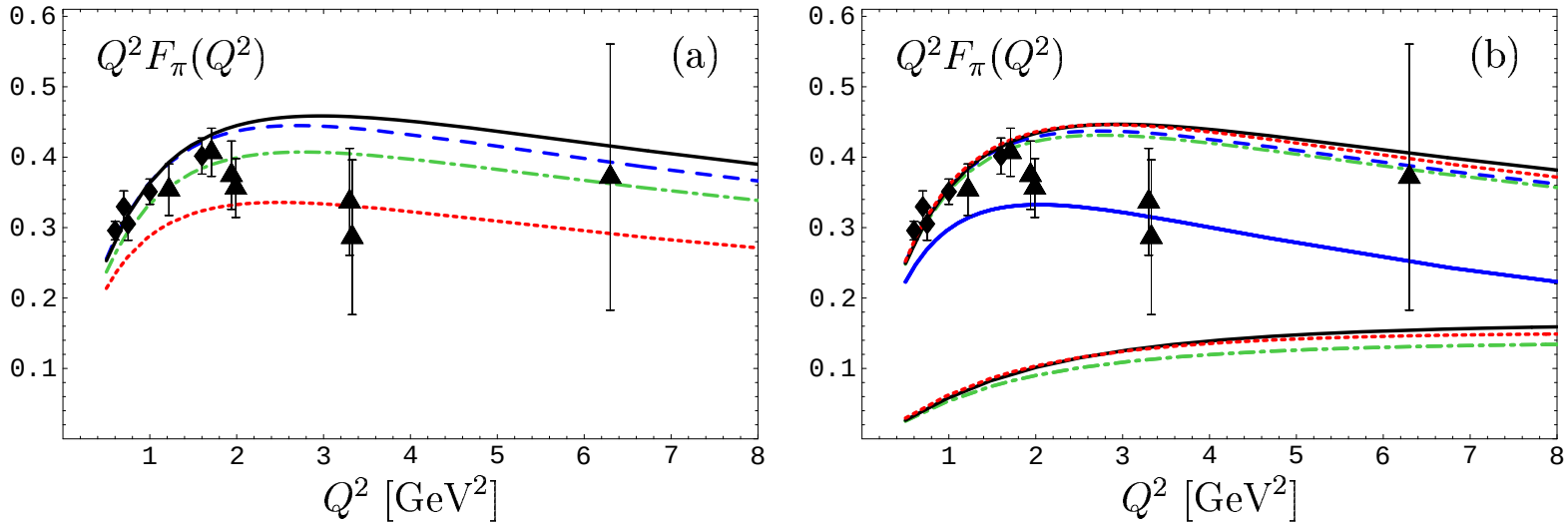
$$F_\pi \to_{Q^2\to\infty} \frac{8\pi\alpha_s f_\pi^2}{Q^2}$$

This asymptotic normalization does **not** exist in the case of the nucleon form factors.

Intermediate Q^2 Scattering Picture:

At experimentally accessible Q^2, the situation is more complicated

Both soft and hard components contribute.



[Bakulev, Passek-Kumericki, Schroers and Stefanis, hep-ph/0405062]

The soft contributions are poorly known, as is the interplay between the soft and hard contributions

[Braun, Khodjamirian, Maul, PRD **61**(00)073004.]

Determination of $\mathbf{F_\pi}$ via Pion Electroproduction

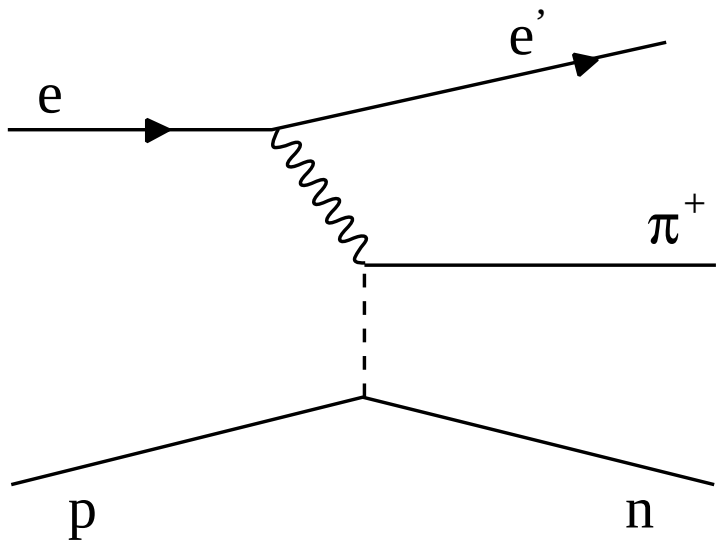
In the timelike region, F_π is determined from the $e^+e^- \to \pi^+\pi^-$ reaction. Our interest is in the spacelike region.

Up to $Q^2 = 0.3$ GeV^2, F_π is measured directly from the scattering of 300 GeV pions from atomic electrons. These data determine the charge radius of the pion, 0.657 ± 0.012 fm.

To access higher Q^2, one must employ the ^{1}H$(e, e'\pi^+)n$ reaction.

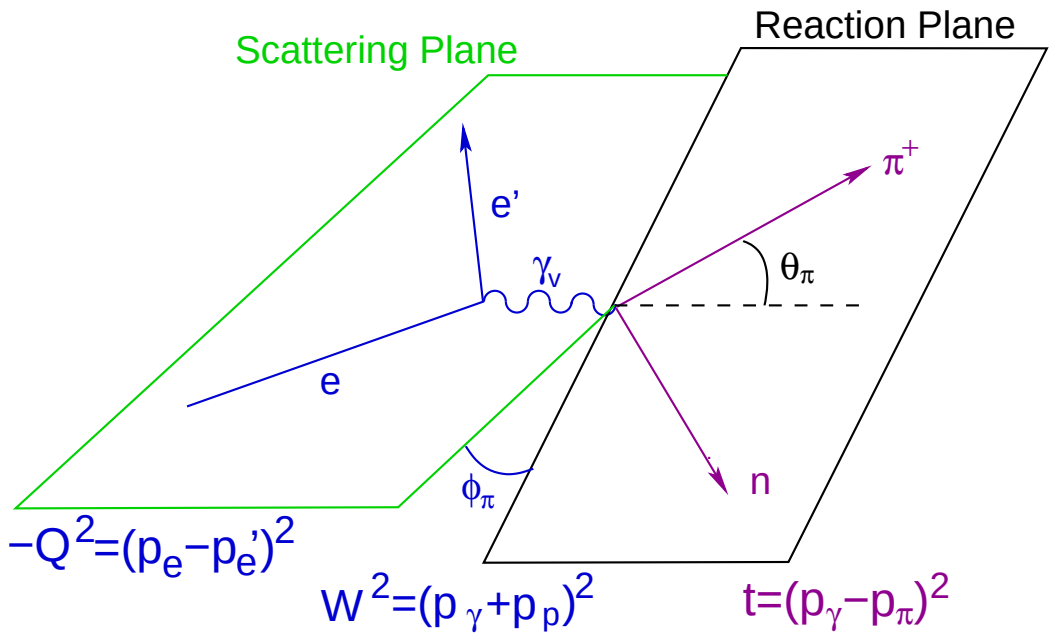
- At small $-t < 0.2$ GeV^2, the t-channel diagram dominates σ_L.
- In the t-pole approximation, $\mathbf{\frac{d\sigma_L}{dt} \propto F_\pi^2}$.

  $\Rightarrow$ In the actual extraction, a model incorporating the π^+ production mechanism and the effects of the 'spectator' nucleon is used to extract F_π from σ_L.



$\Rightarrow$ π^+/π^- ratios from $^2H(e, e'\pi)$ are measured to test the validity of t-pole dominance and the model used.

What type of data do we need?



$$2\pi\frac{d^2\sigma}{dtd\phi} = \epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}cos2\phi$$

1. Take data at the smallest available $-t$, so that σ_L has maximum contribution from the π^+ pole.

   $\Rightarrow$ For a given Q^2, higher W allows smaller $|t|_{min}$.

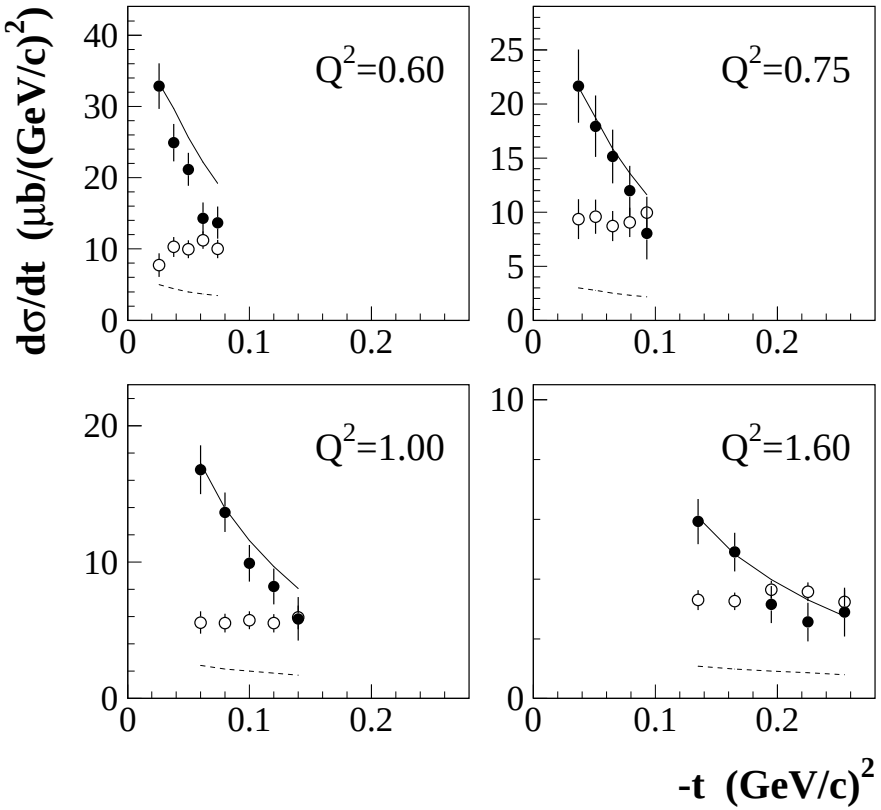
2. The extraction of F_π from σ_L requires that the $-t$ dependence of $d\sigma_L/dt$ is known.

   $\Rightarrow$ Only three of W, Q^2, $-t$, and θ_π are independent.
   Vary θ_π to obtain $-t$ dependence of the data.

   $\Rightarrow$ Since non-parallel data are needed, TT and LT must also be determined by the experiment.

Extraction of F_π from σ_L data

$Q^2 = 0.70$ GeV^2 DESY expt [Z.Phys.C **3**(79)101] used a Born term (BT) model, with modification to improve the description of the t-dependence of the data.



JLab expts use the Vanderhaeghen, Guidal and Laget Regge model, which provides a better treatment of the t-dependence.

"Model uncertainty" of extracted F_π result is obtained from fit to the t-dependence of the data under various assumptions.

DESY data also reanalyzed using Regge model:

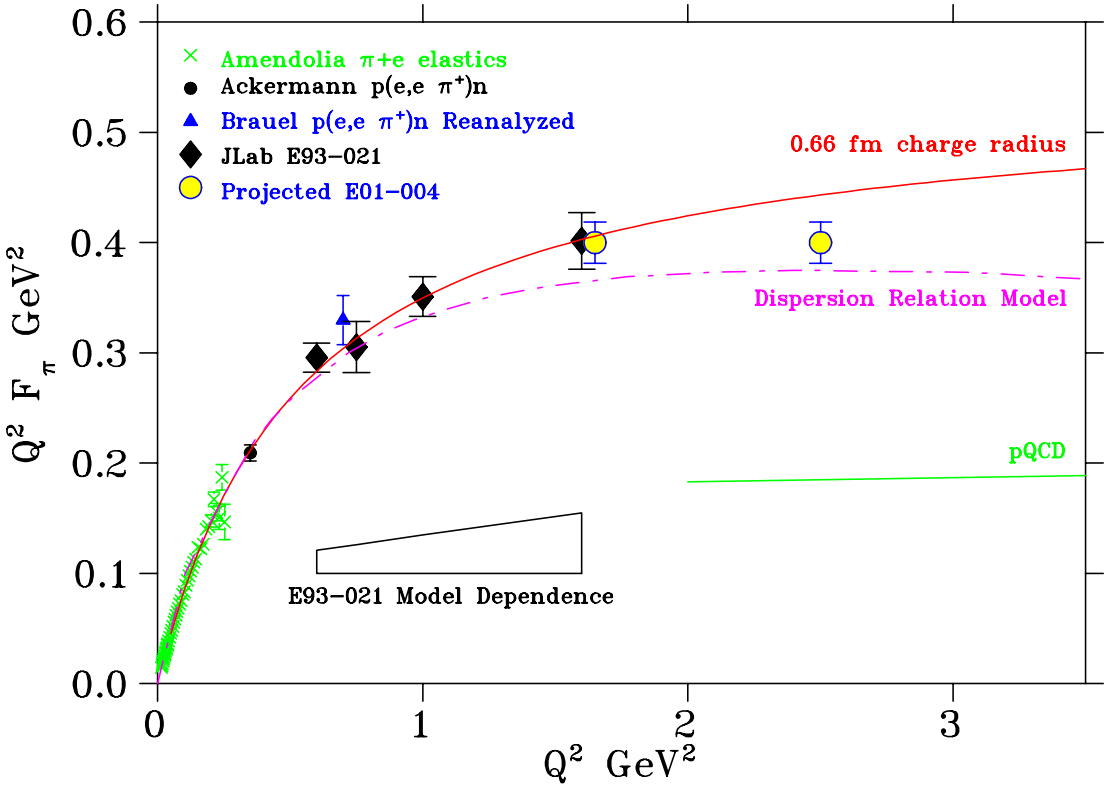
$\Rightarrow F_\pi(Q^2 = 0.70)$

increases by 0.05 from result obtained with BT model.

Recent and projected experimental data

E93-021 data is close to a monopole form factor with 0.657 fm charge radius.

These measurements were recently extended in a new Hall C experiment in the summer of 2003.



- $Q^2 = 2.45$ GeV^2 using 6 GeV electron beam.
- Reduce model uncertainties in F_π extraction by obtaining data at higher $W = 2.21$ GeV.
  $\Rightarrow$ New data will be closer to $t = m_\pi^2$ pole.
  $\Rightarrow$ Regge model can be applied with greater authority, so expect smaller model uncertainties.
- Q^2 region where F_π theoretical calculations begin to diverge.
  $\Rightarrow$ New data will constrain the treatment of soft contributions in QCD-based models.

Expect preliminary data to be released in second-half 2005.

F_π Long Term - 12 GeV Upgrade

The SHMS+HMS in Hall C will allow F_π to be measured to Q^2 =6 GeV^2, and possibly higher, depending on the favorability of the σ_L/σ_T ratio at large Q^2.

The 5.5^o forward angle capability of the SHMS is specifically driven by the requirement of the F_π experiment to access low -t.

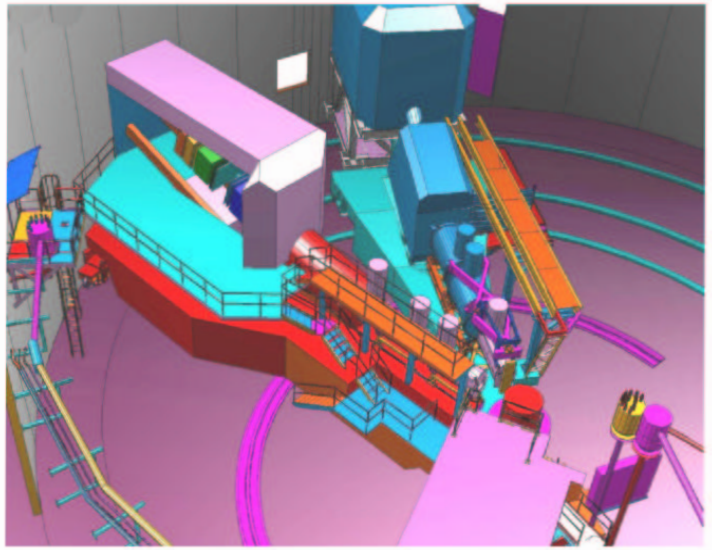
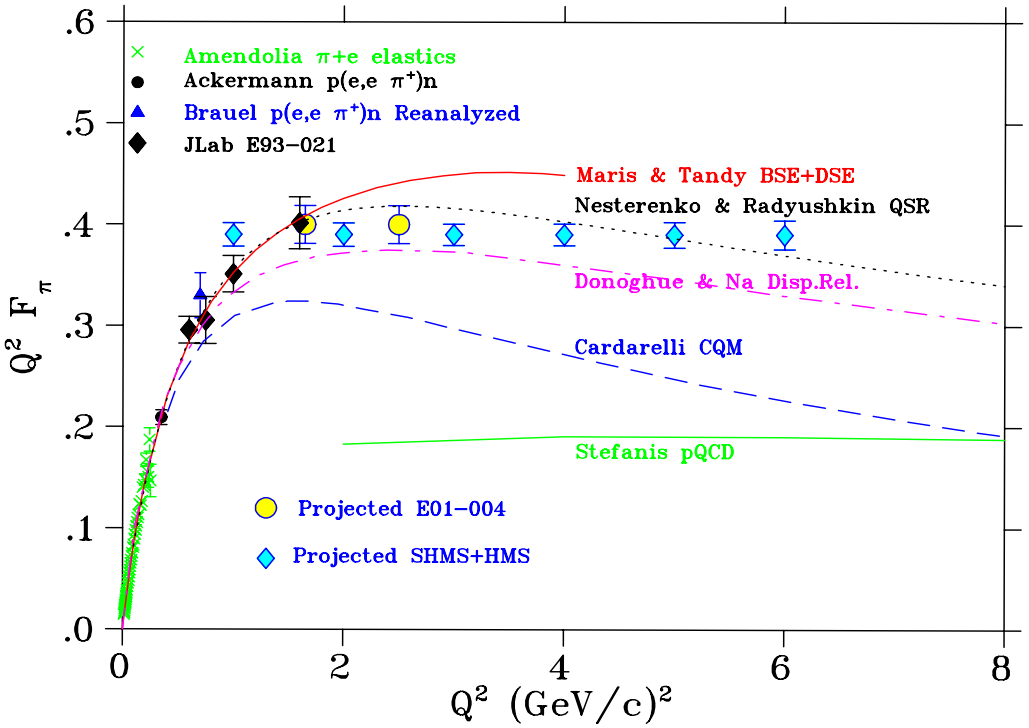


Figure 4.3: Artist's Rendering of SHMS and HMS Spectrometers in Hall C. The top of the SOS Spectrometer is in the foreground.



These higher Q^2 data will have an unprecendented ability to test the state-of-the-art QCD calculations anticipated by that time.

Quasi-free pion production on ^{2}H.

Compare π^- and π^+ production

At low $|t|$: t-pole approximation: coupling to π^- or π^+

$$\Rightarrow R_{\pi^-/\pi^+} = 1.0$$

(isoscalar amplitudes are zero)

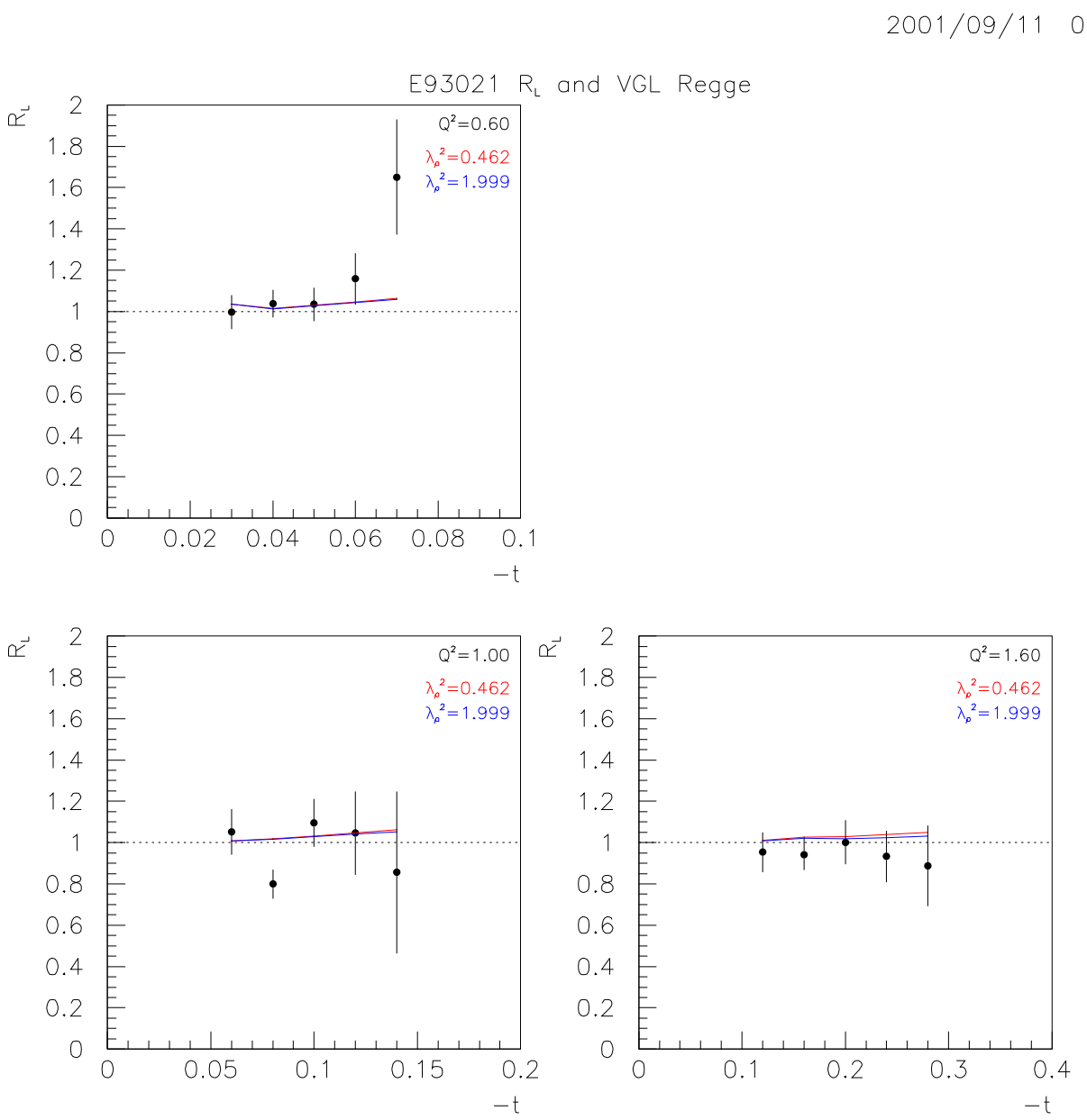
At high $|t|$: coupling to (charge of) quarks?

$$R_{\pi^-/\pi^+} = 1/4\,?$$

Q^2 dependence ?

L, T dependence ?

Preliminary results from Fpi1 (93-021) (Vardan Tadevosyan)



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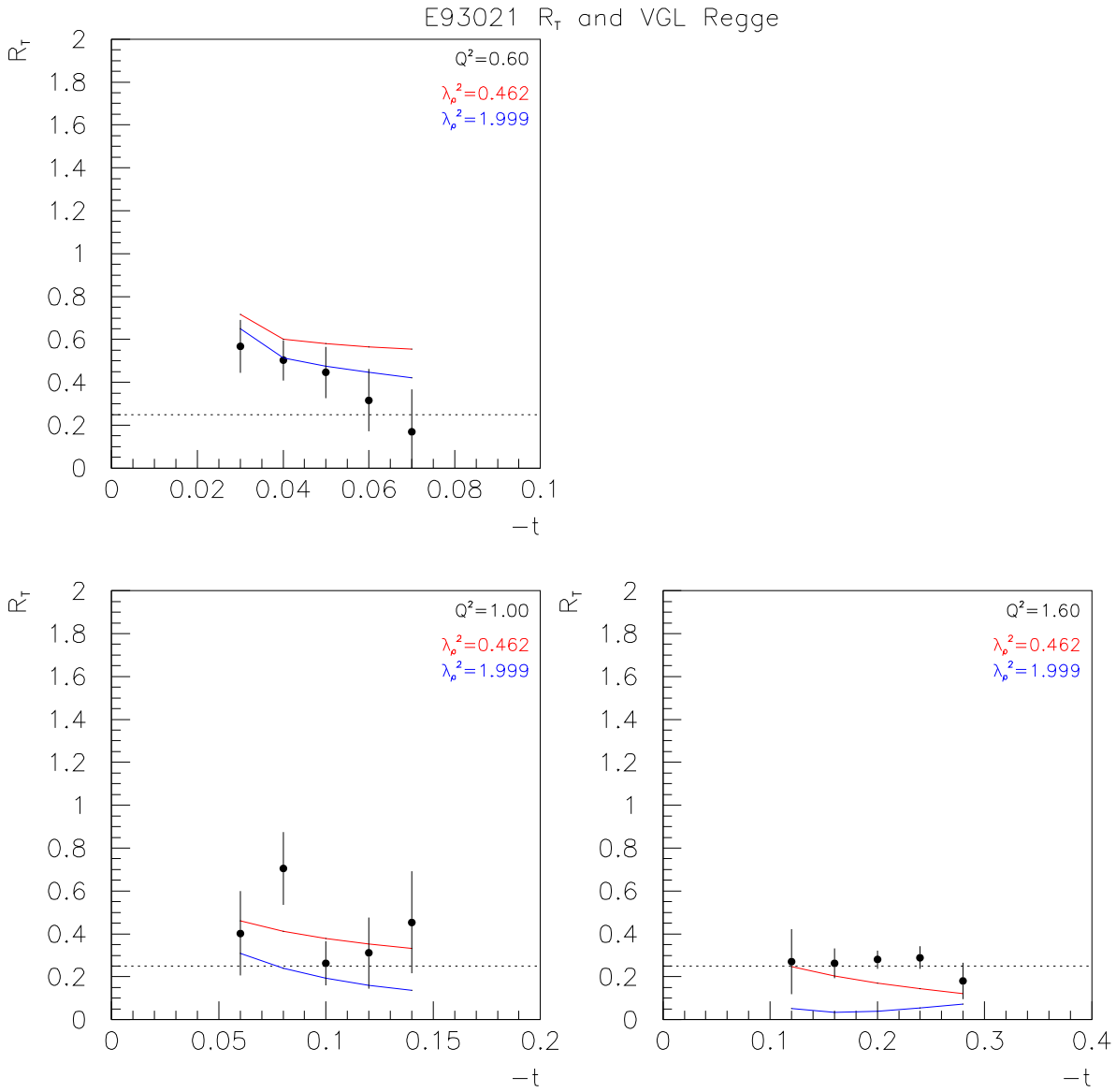
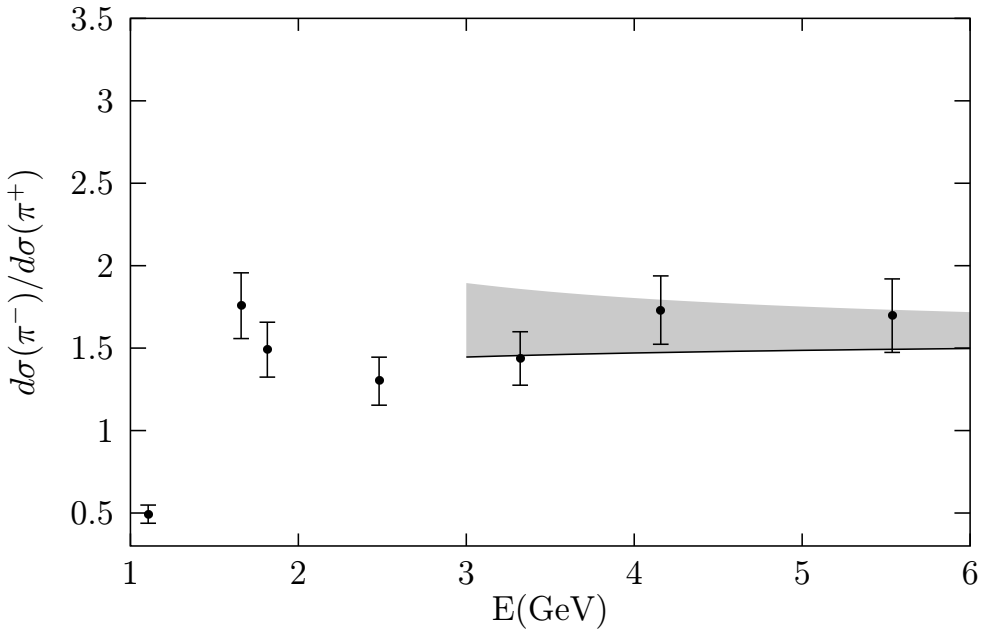


Pion production at high $|t|$.

Hall A results for photoproduction on ^{2}H.

Calculations by Huang, Jakob, Kroll and Passek-Kumericki

(hep-ph/0309071, Eur.Phys.J. C33 (2004) 91)



Suggests factorization into (non pQCD) photon-quark vertex and GPD.

^{1}H(e,e′π^+)n at high $|t|$.

Very preliminary results from a 'first look'.

Calculations by Jean-Marc Laget (hep-ph/0406153)